Thoughts on the Pseudogap

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Outline

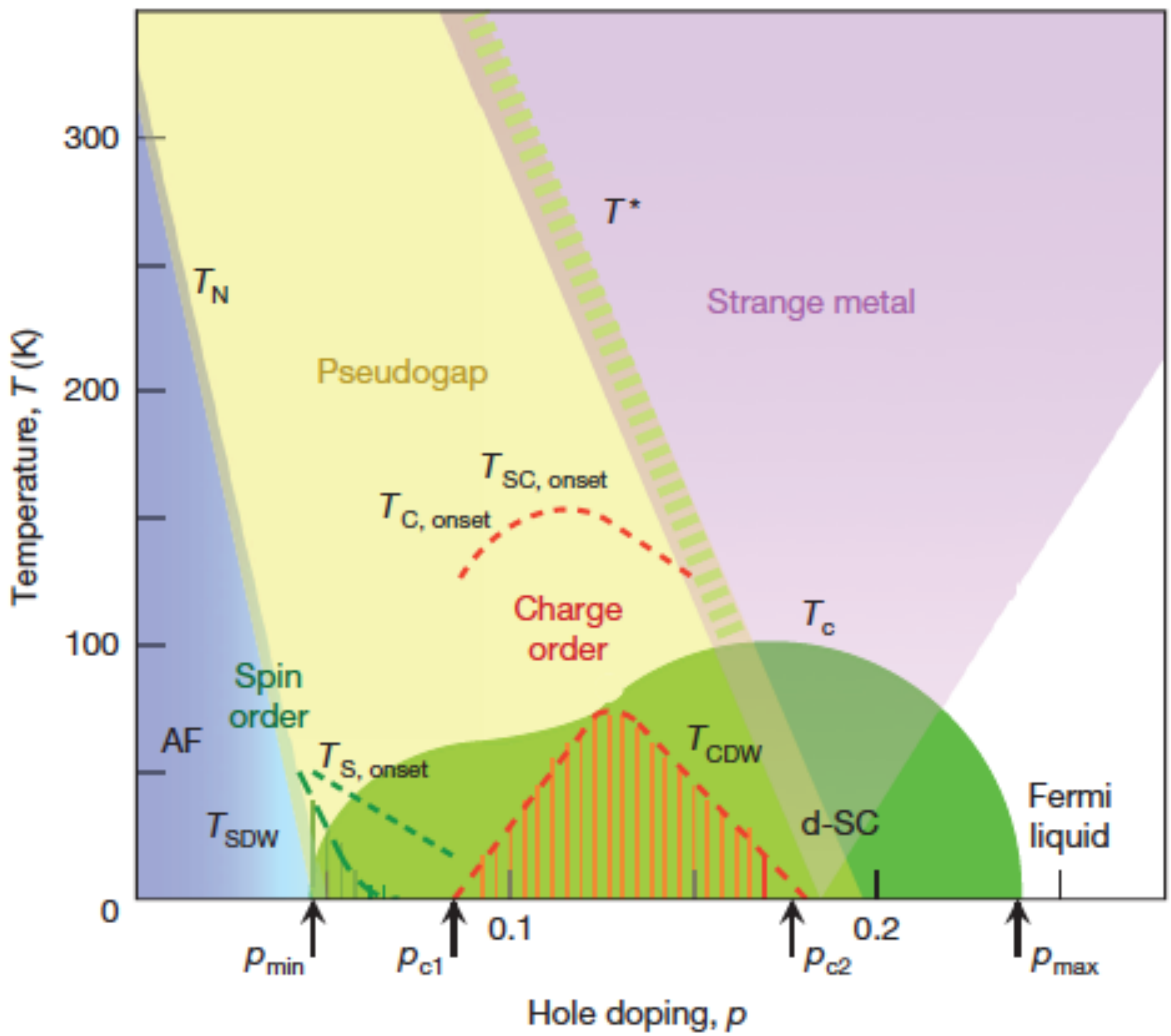
1. Impact of pseudogap on spin fluctuation mediated pairing

   Mishra, Chatterjee, Campuzano, Norman, Nature Physics 10, 357 (2014)

2. d-wave charge order from spin fluctuations

   Mishra and Norman, arXiv:1502.02782v2 (to appear, Phys Rev B)

Phase Diagram of the Cuprates



Keimer *et al*, Nature (2015)

What is the Pseudogap Due to?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

$$\boxed{A(k,\omega) = I(k,\omega) + I(-k+2k_F,-\omega)}$$ (spectral function)

$$\boxed{\chi_0(q,\Omega) = \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty} d\omega' \frac{f(\omega)-f(\omega')}{\omega-\omega'+\Omega+i0^+}\frac{1}{N}\sum_k A(k+q,\omega)A(k,\omega')}$$ (p-h bubble)

$$\boxed{\chi(k,\Omega) = \frac{\chi_0(k,\Omega)}{1-U\chi_0(k,\Omega)}}$$ (dynamic susceptibility)

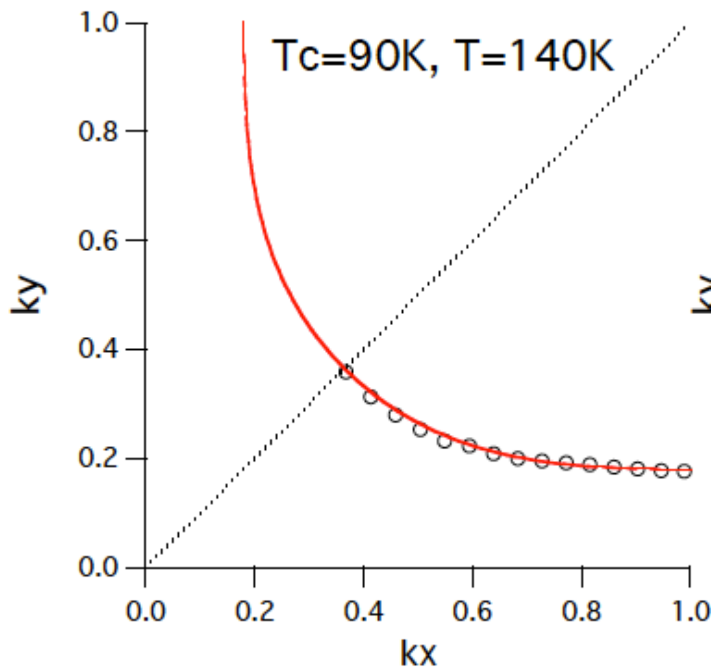
$$\boxed{V(k,\Omega) = \bar{U}^2\left[\frac{3}{2}\chi(k,\Omega) - \frac{1}{2}\chi_0(k,\Omega)\right]}$$ (pair potential)

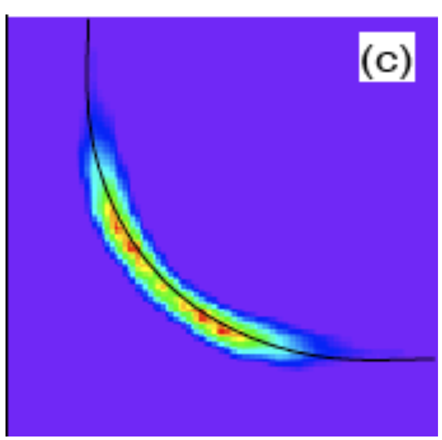
$$\boxed{\Sigma(k,i\omega_n) = T\sum_{q,\omega_m} V(k-q,i\omega_n-i\omega_m)G_0(q,i\omega_m)}$$ (normal self-energy)

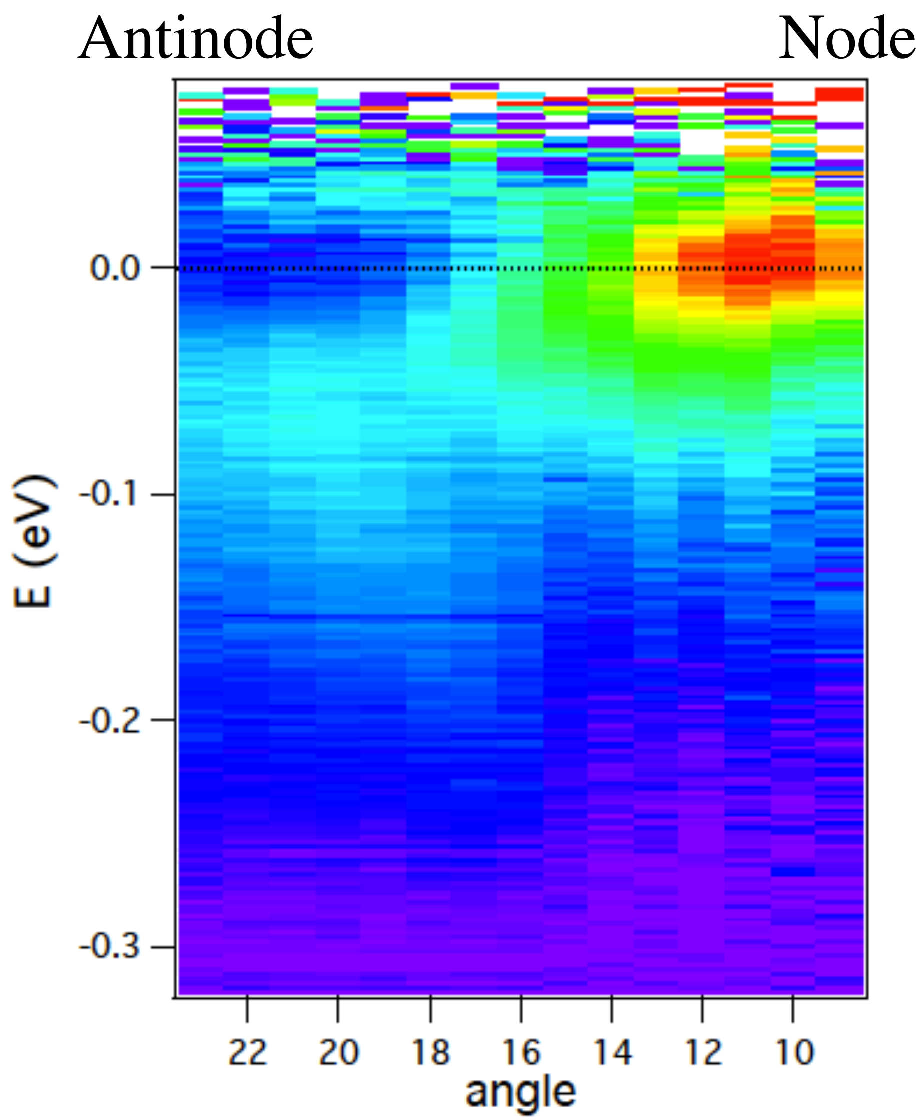
$$\boxed{-\frac{T}{N}\sum_{k',\omega_m} V(k-k',i\omega_n-i\omega_m)\mathcal{P}_0(k',i\omega_m)\Phi(k',i\omega_m) = \Phi(k,i\omega_n)}$$ (gap equation)

$$\boxed{\mathcal{P}_0(k',i\omega_m) = G(k',i\omega_m)G(-k',-i\omega_m)}$$ (pairing kernel)

ARPES data from a Bi2212 single crystal (T_c=90K, T=140K)

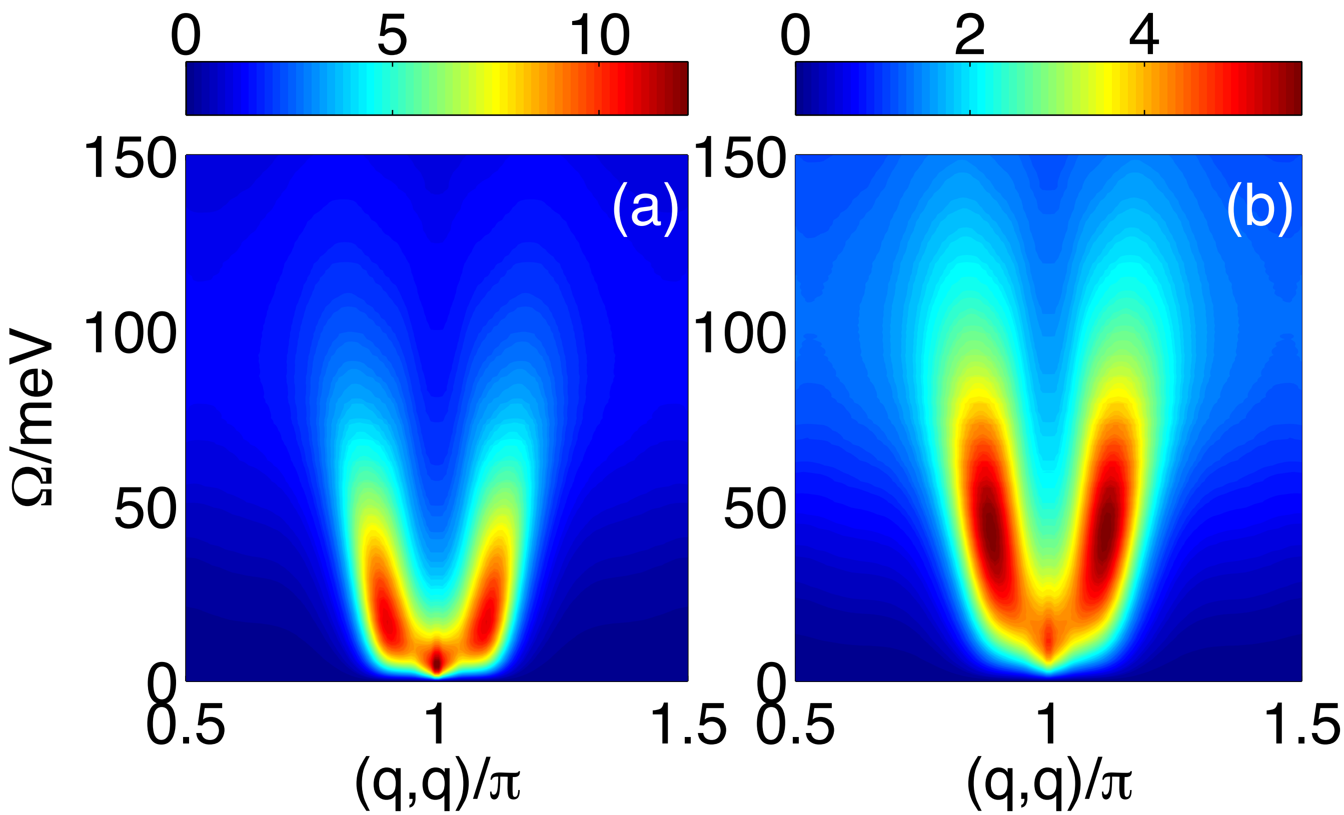




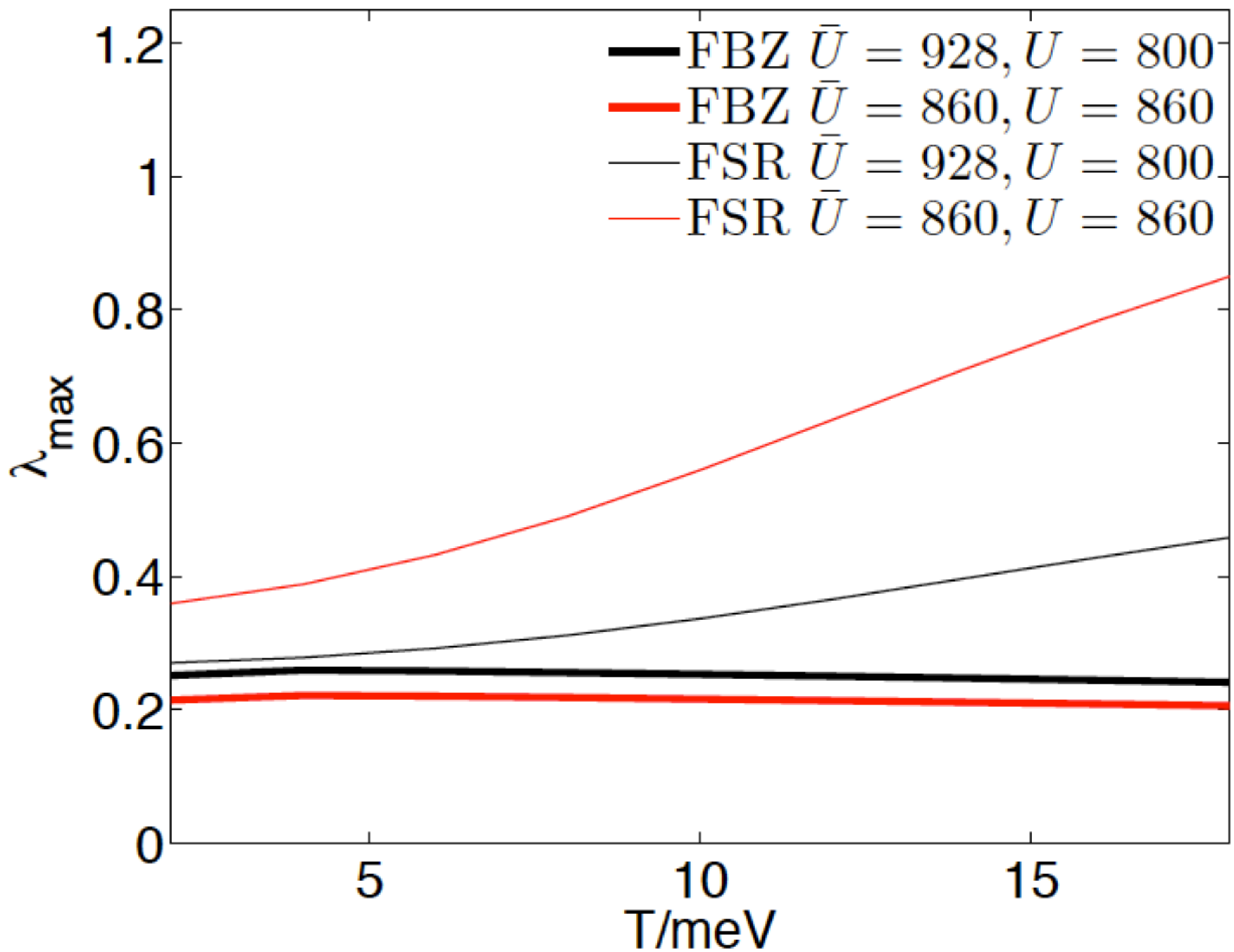


Kaminski *et al*, PRL (2001)

$\chi(q,\omega)$ for U = 860 meV (left) and 800 meV (right)
using ARPES Greens functions



d-wave eigenvalue versus temperature using ARPES Greens functions
(FBZ is full Brillouin zone, FSR is Fermi surface restricted)



$$\boxed{-\frac{T}{N_\phi}\sum_{\phi',\omega_m} V_{nm}^{\phi\phi'}\mathcal{P}_0(\phi', i\omega_m)\Phi(\phi', i\omega_m) = \Phi(\phi, i\omega_n)}$$

(FS restricted gap equation)

$$\boxed{V_{nm}^{\phi\phi'} = V(k_{Fx}^{\phi} - k_{Fx}^{\phi'}, k_{Fy}^{\phi} - k_{Fy}^{\phi'}, i\omega_n - i\omega_m).}$$

(FS restricted pair interaction)

$$\boxed{T\sum_{\omega_n}\int_0^{2\pi}\frac{d\phi}{2\pi}\mathcal{V}\cos^2(2\phi)P_0(\phi, i\omega_n) = 1.}$$

(weak coupling gap equation)

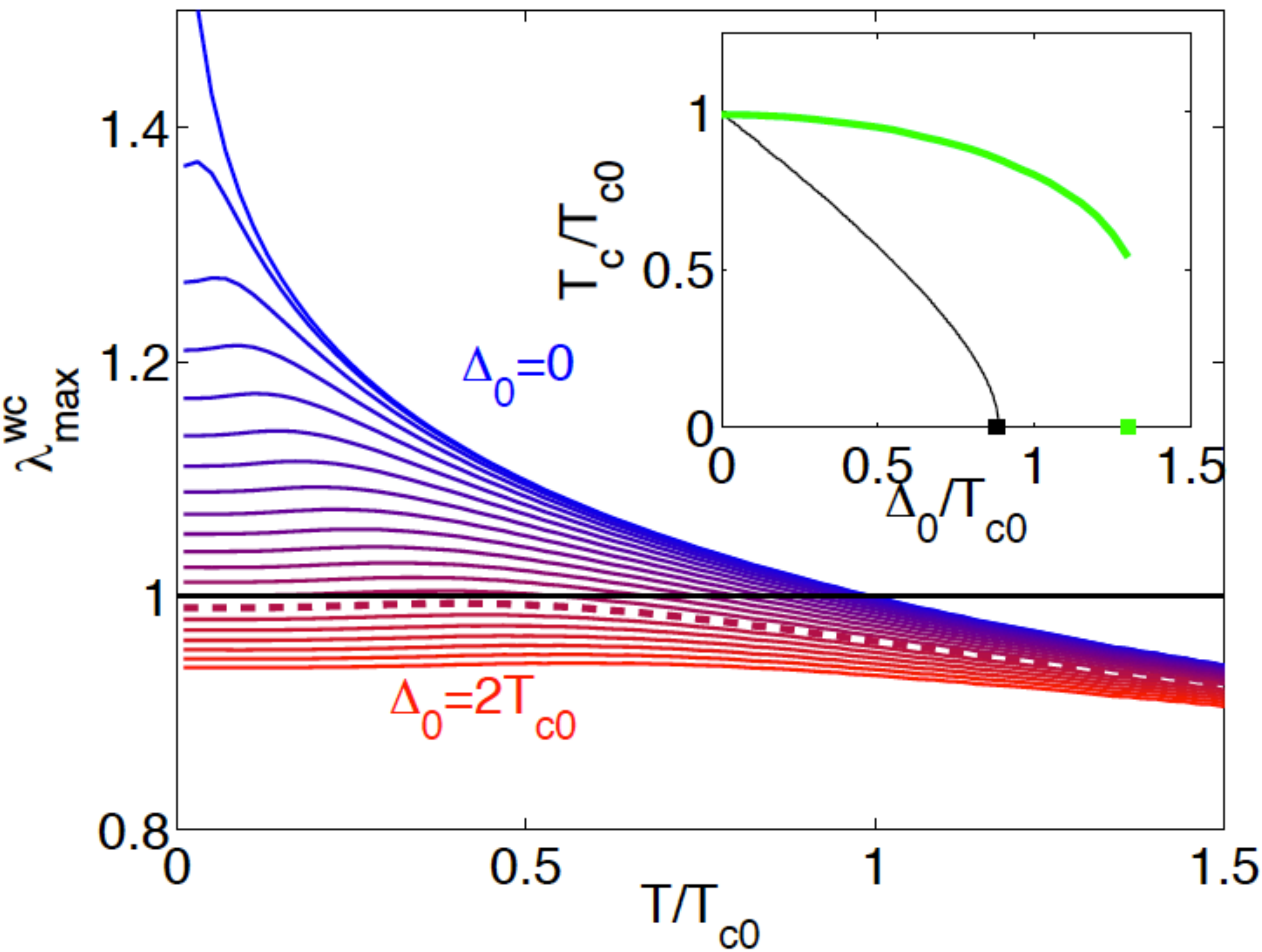
$$\boxed{G(k, i\omega_n) = -\frac{i\omega_n + i\Gamma sgn(\omega_n) + \xi_k}{(\omega_n + \Gamma sgn(\omega_n))^2 + \xi_k^2 + \Delta_k^2}.}$$

(model Greens function)

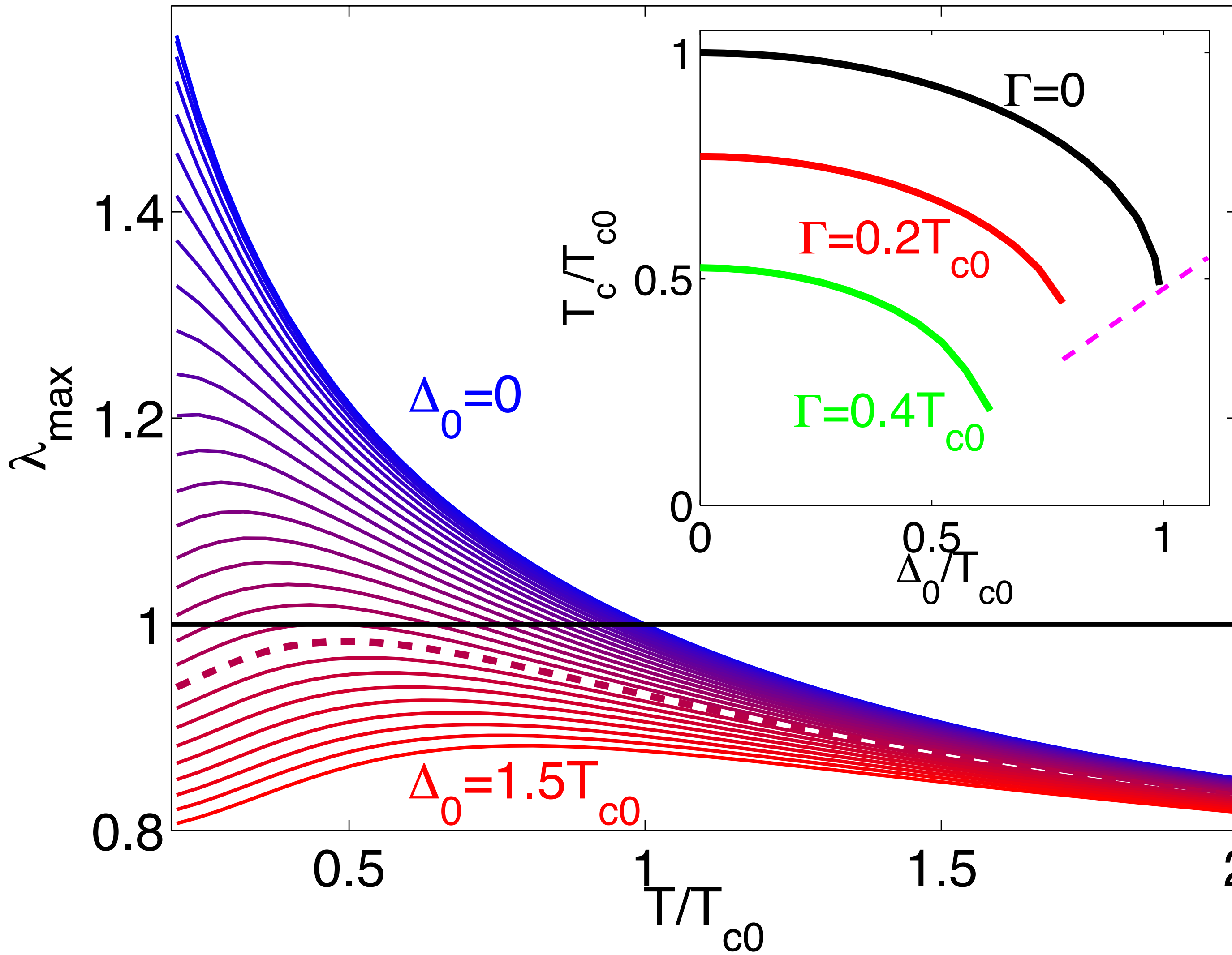
$$\boxed{V(k,\Omega) = \frac{3}{2}g_{sf}^2\frac{\chi_{\mathbf{Q}}}{\xi_{AF}^{-2} + 2 + \cos k_x + \cos k_y - i\frac{\Omega}{\Omega_{sf}}}}$$

(MMP pair interaction)

Weak coupling d-wave eigenvalue vs T for various pseudogaps Δ_0
[inset is T_c versus Δ_0 (green curve) and T_c vs Γ (black curve)]



T_c vs pseudogap (Δ_0) for various Γ using MMP pair interaction (inset)
[dashed line is temperature maximum of λ vs Δ_0 for Γ=0]
d-wave eigenvalue λ vs T for various Δ_0 (main panel)

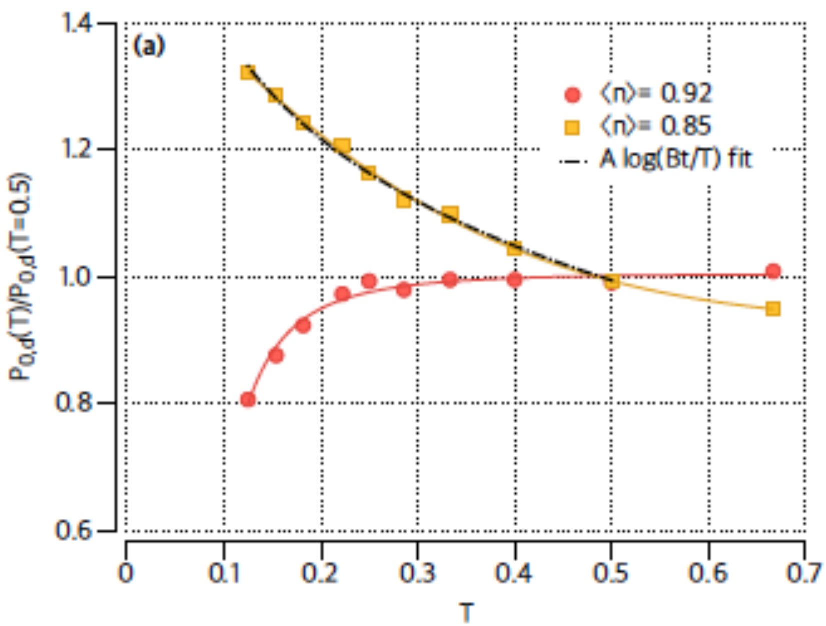


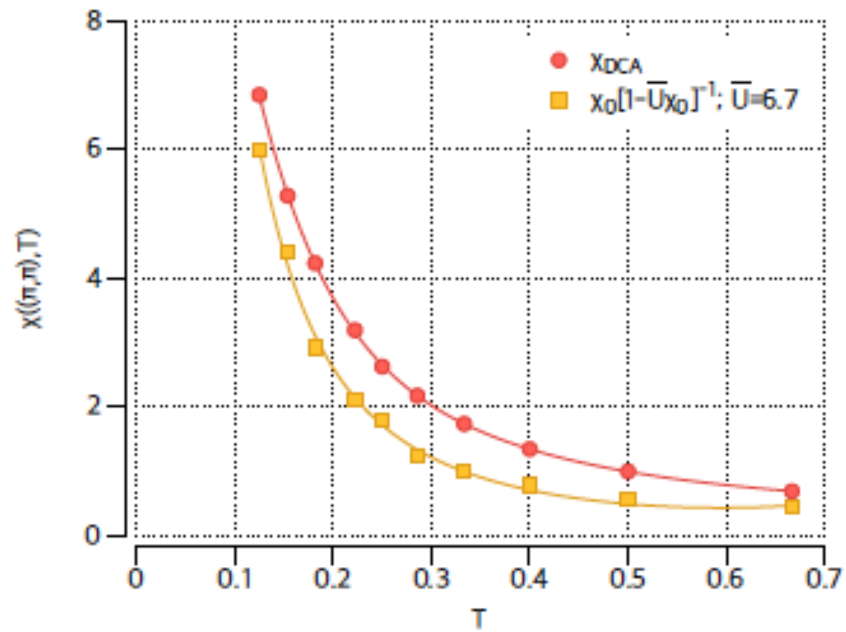
CONCLUSION (part 1)

Pair breaking effect of the pseudogap is so strong that T_c should be suppressed to zero UNLESS the pseudogap itself is due to pairing

OR

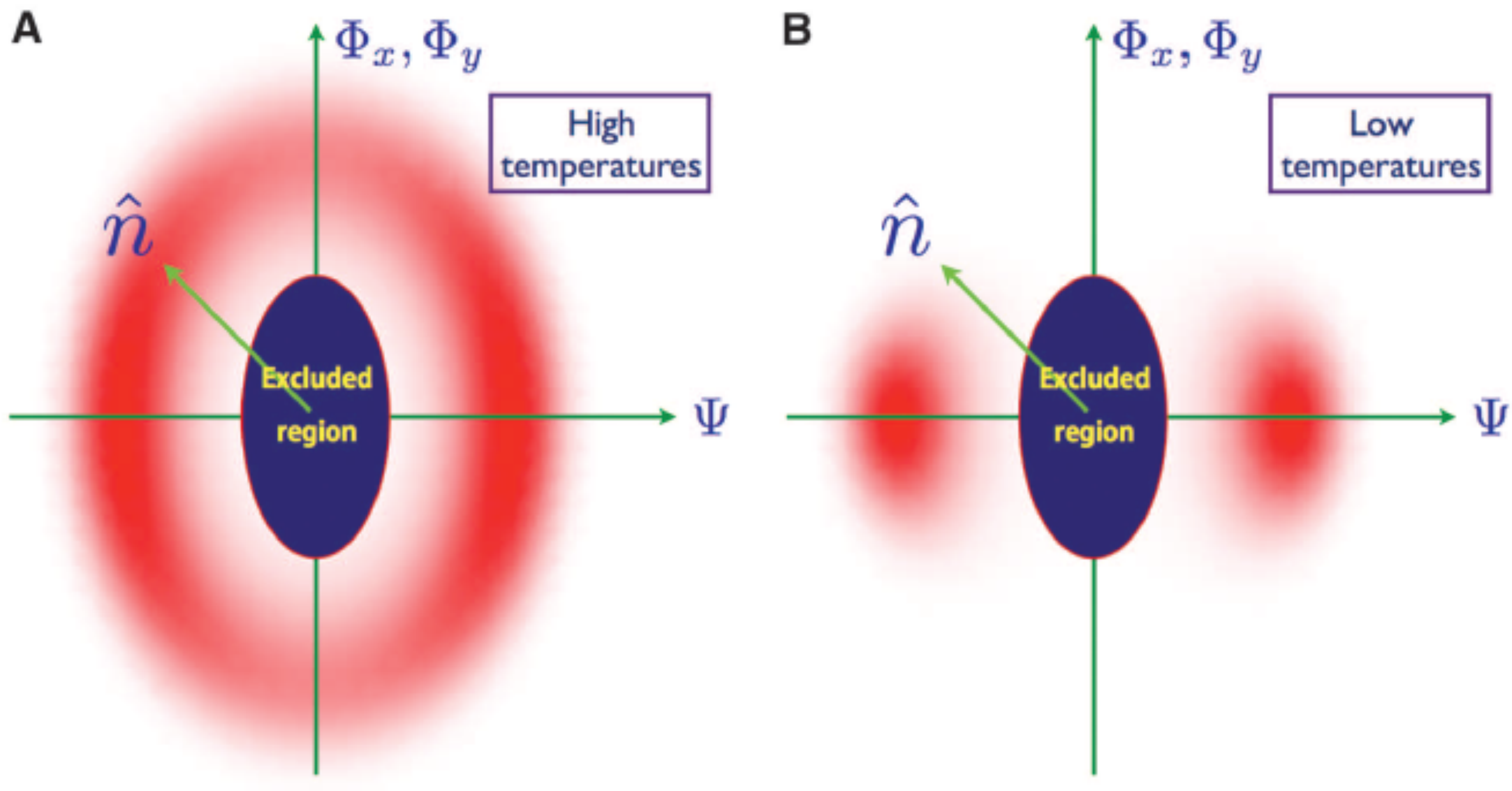
the transition is driven instead by the T dependence of the interaction





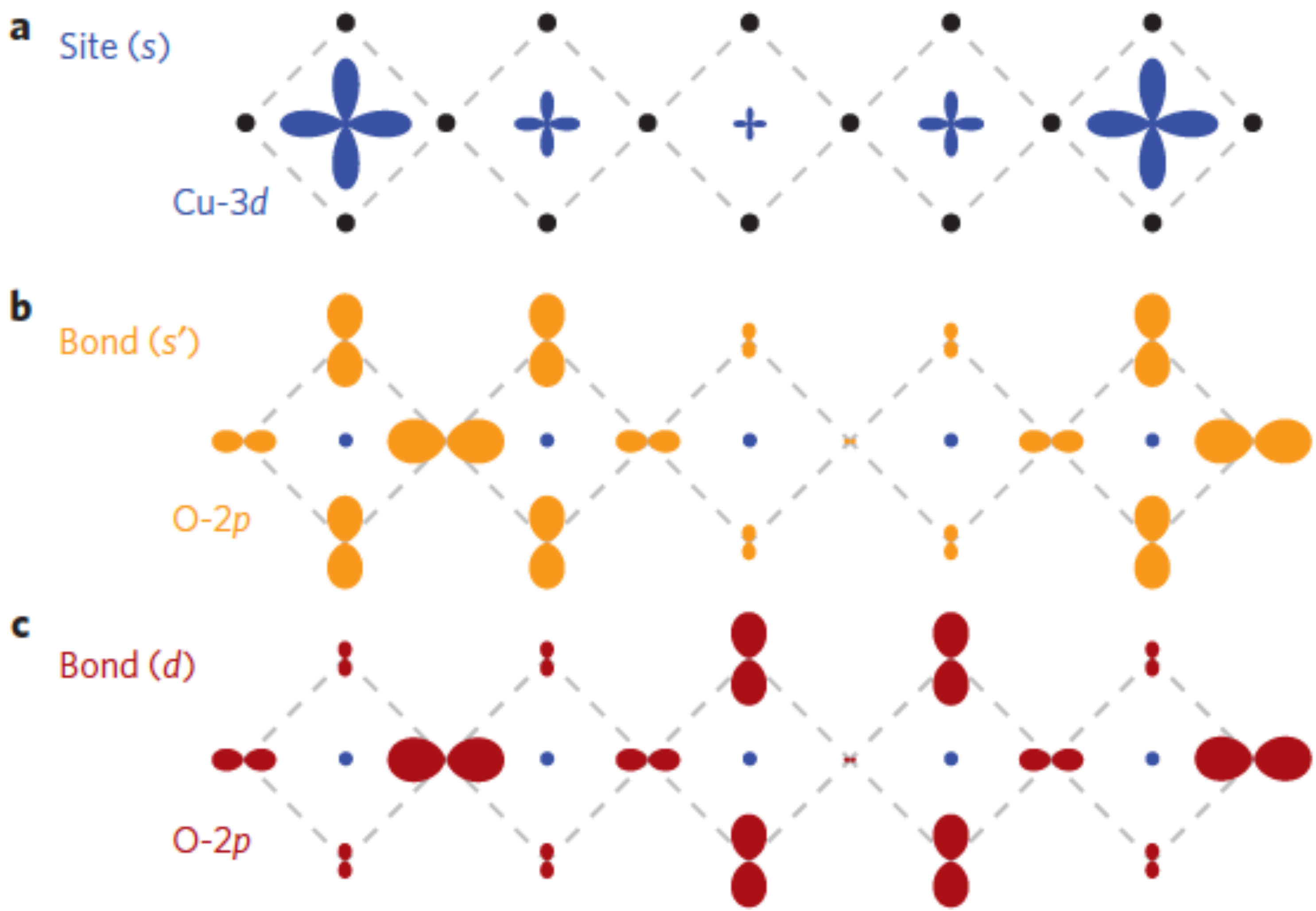
Maier, Staar, Scalapino, arXiv:1507.06206

d-wave superconductivity and d-wave charge order
Two sides of the same coin?



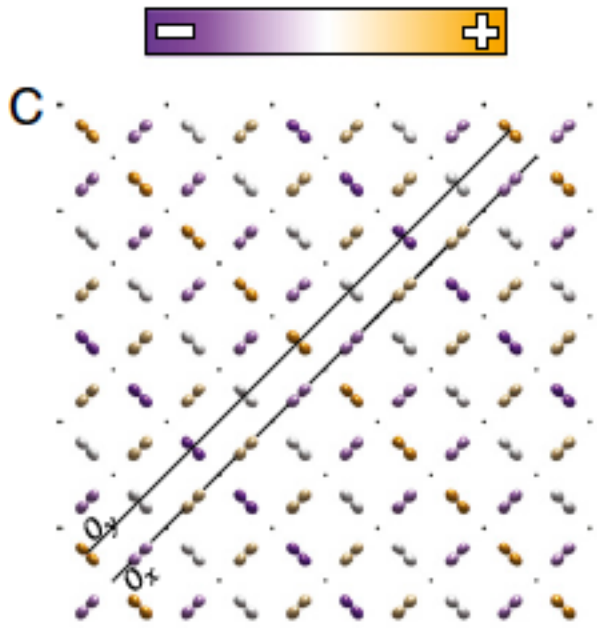
Hayward *et al*, Science (2014)

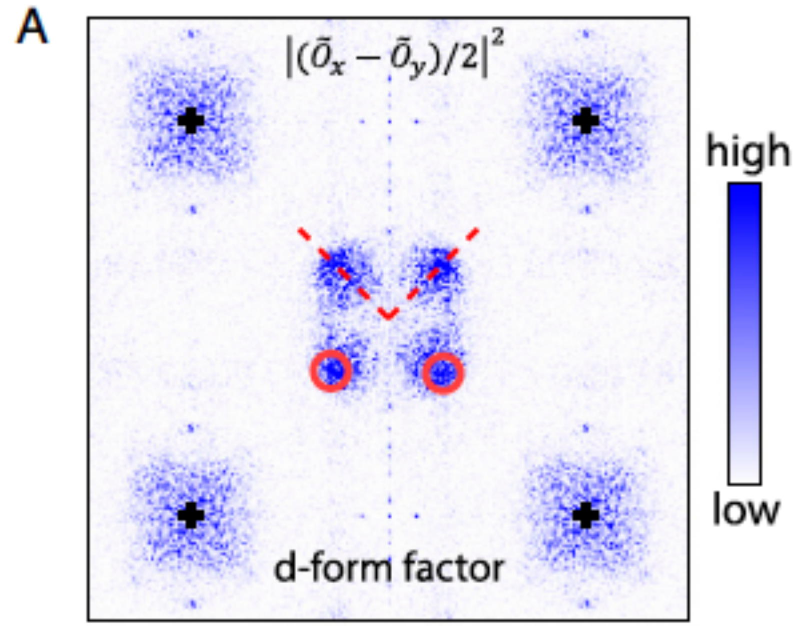
The work of Sachdev and others has motivated new experiments designed to look for d-wave charge order by x-rays and STM



Comin *et al*, Nature Matls. (2015)

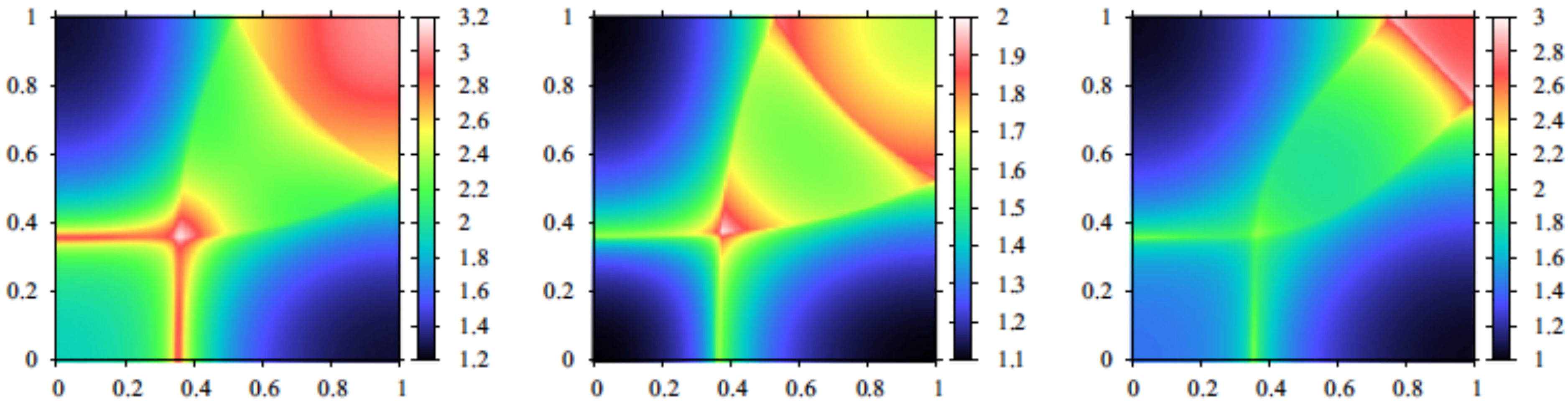
Fourier STM



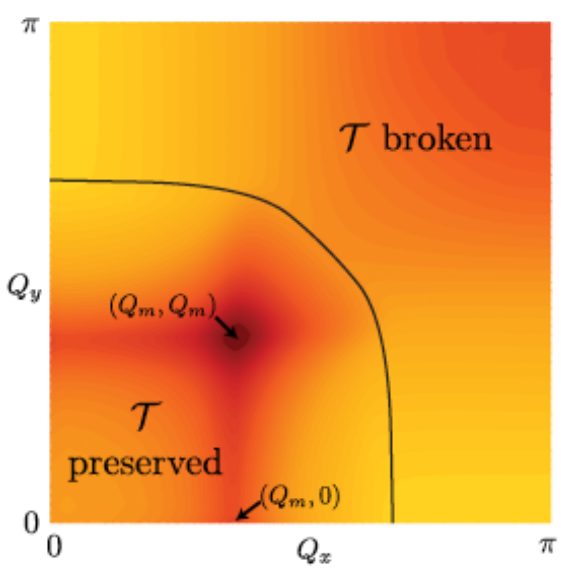


Fujita *et al*, PNAS (2014)

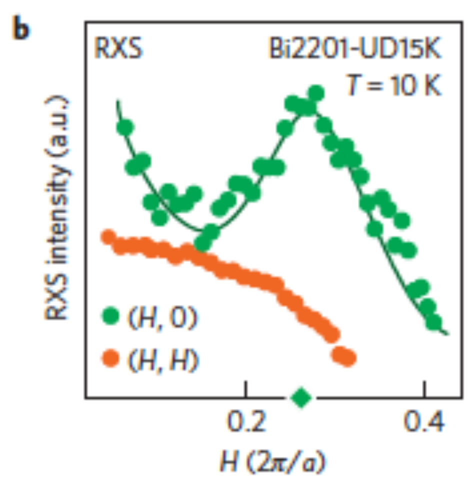
Problem 1 – itinerant models tend to predict diagonal (Q,Q) order



Norman, PRB (2007); Melikyan & Norman, PRB (2014)

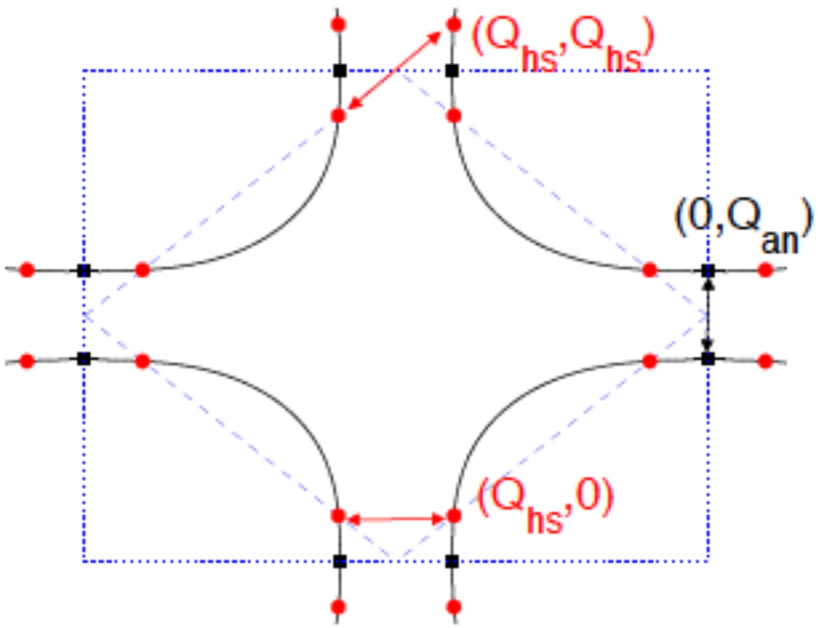


Sachdev & La Placa, PRL (2013)



Comin *et al*, Nature Matls. (2015)

Problem 2 – itinerant models typically rely on nesting/hot spots



To address this, we will solve full Brillouin zone strong coupling eqs.

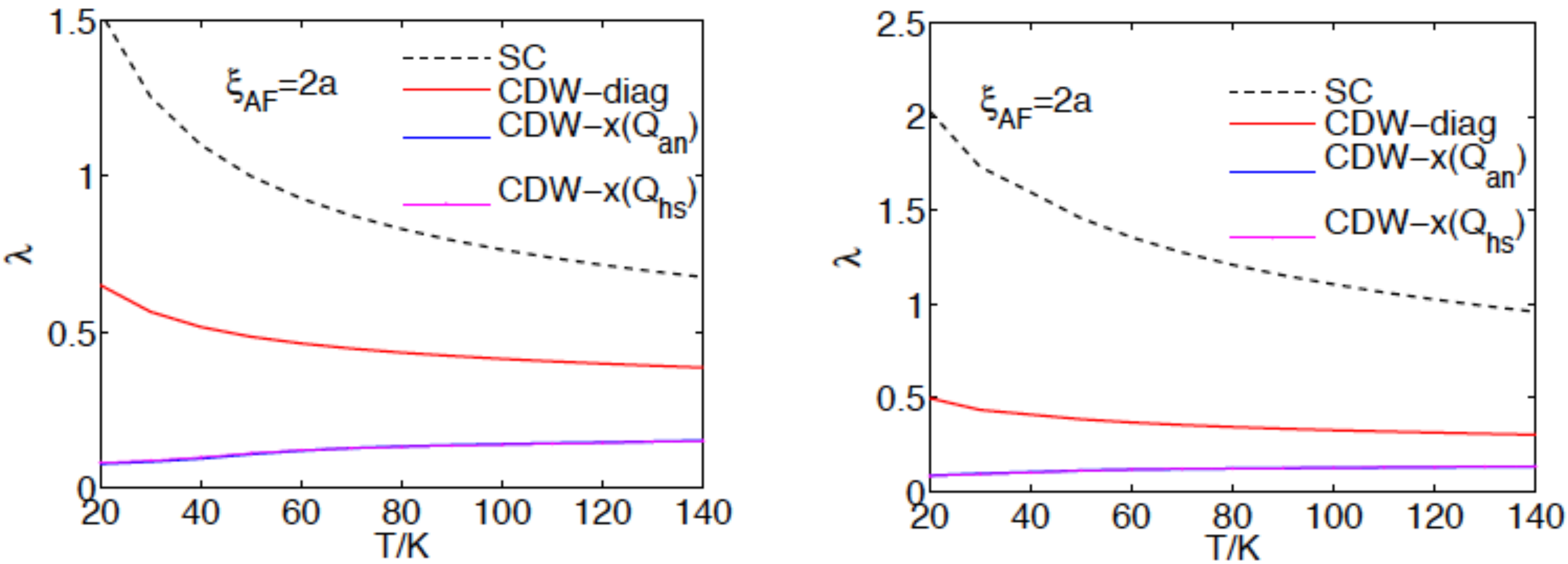
$$\boxed{T\sum_{k',\omega_m} V(k-k',i\omega_n - i\omega_m)G(k'-\frac{Q}{2},i\omega_m)G(k'+\frac{Q}{2},i\omega_m)\Phi^Q(k',i\omega_m) = \lambda\Phi^Q(k,i\omega_n)}$$

$$\boxed{V(k,\Omega) = \frac{3}{2}g_{sf}^2\frac{\chi_Q}{\xi_{AF}^{-2}+2+\cos k_x+\cos k_y+i\frac{\Omega}{\Omega_{sf}}}}$$

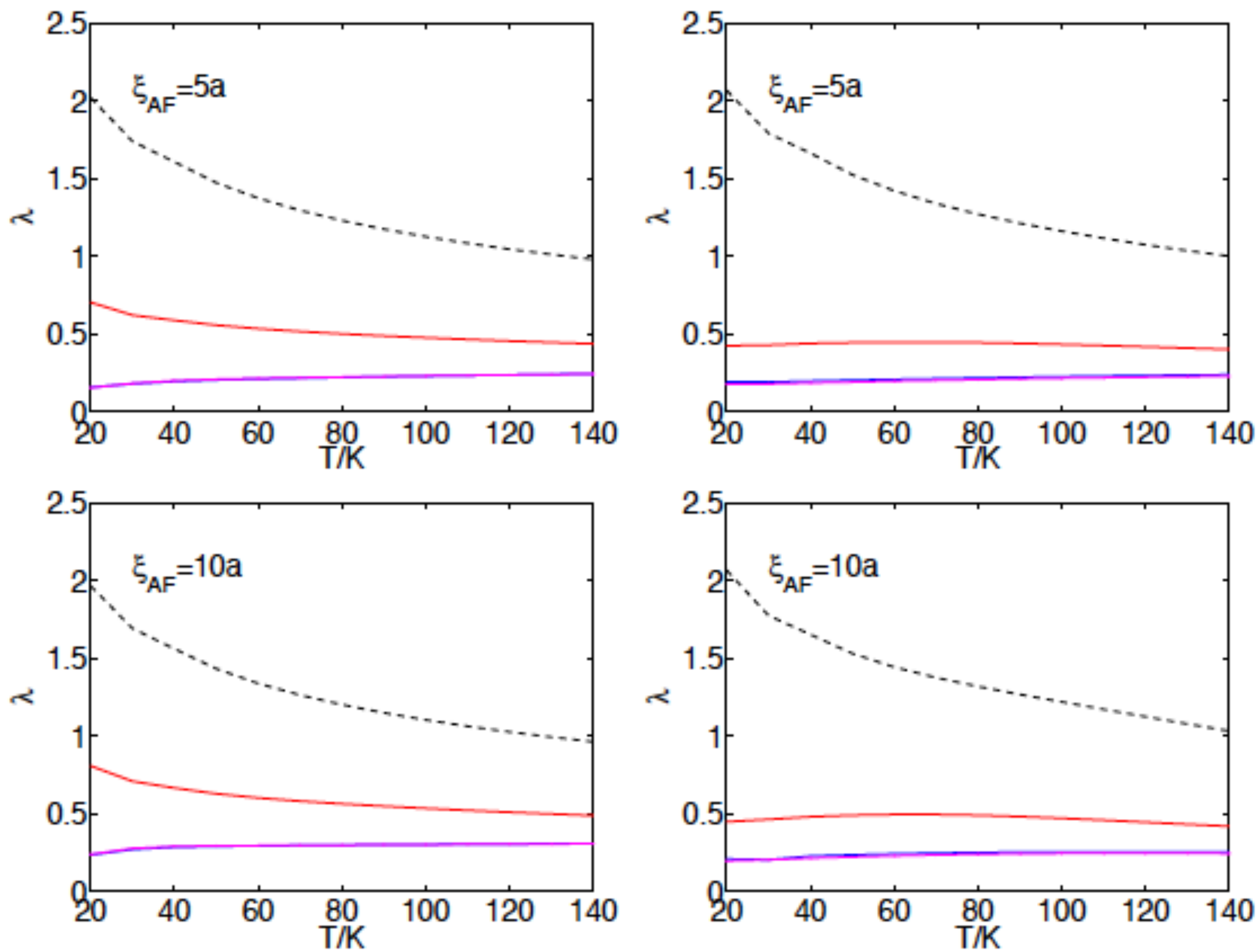
$g_{sf}^2\chi_Q$ – adjusted to get d-wave superconducting T_c
Ω_{sf} – set by energy scale of spin fluctuations (RIXS, INS)
ξ_{AF} – set by q dependence of spin fluctuations (INS)

G – (1) bare G, but based on renormalized dispersion from ARPES
(2) full G dressed by spin fluctuations

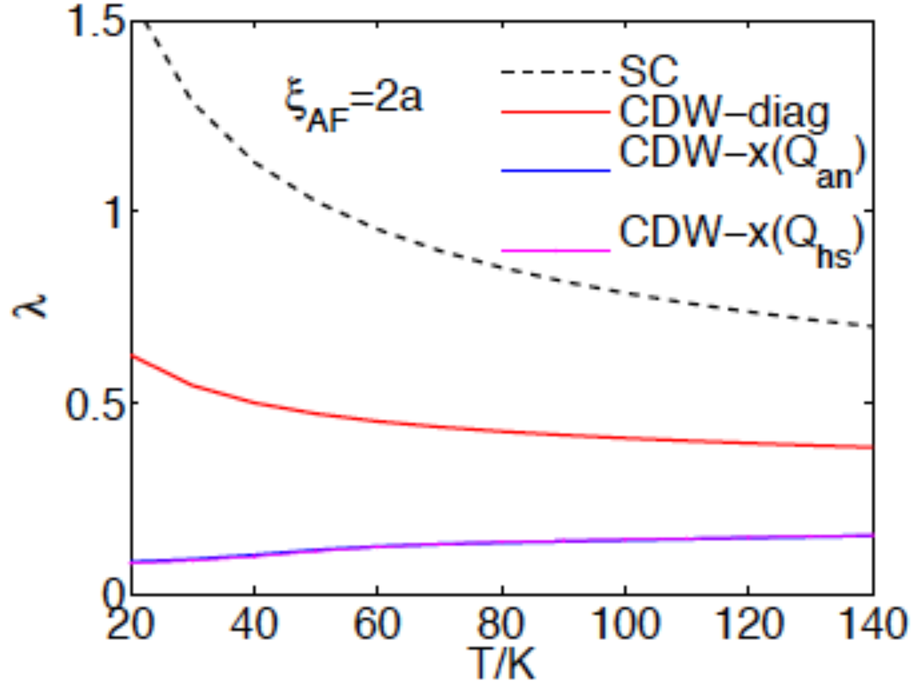
Strong coupling calculations using a renormalized bare Greens function do not find bond charge order (left); using a fully dressed G leads to an additional suppression of diagonal charge order as well (right)



Going to longer antiferromagnetic correlation lengths does not really change the story



Inclusion of a modest coupling to B_{1g} phonons does not help either



CONCLUSION (part 2)

An itinerant model for the charge order is unlikely

The d-wave order is likely due to Coulomb repulsion
between the doped holes on the oxygen sites,
with each unit cell maintaining the same hole count